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Productivity Study of WoodPac Bundling of Logging Residues and Small Stems

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Abstract

A new approach for procuring logging residues has been introduced, in which the residues are compacted into cylindrical bales known as composite residue logs (CRLs). Some large-scale productivity studies have been undertaken on different bundling machines, and preliminary calculations on the possible benefits associated with bundling have been based on limited material or on prototypes.

The aims of the study presented here were to measure the effects of concentrating forest fuel on bundling productivity with a WoodPac machine and to test if there was a difference between bundling logging residues and small stems.

The results show that the WoodPac machine produced 19.3 bundles per effective hour (E_0), equivalent to 28.5 MWh, in a clear-cut spruce stand. Productivity was not influenced by the amount of green mass as long as there was more than 5 Mg per 100 m driving distance and the material was collected in heaps. About 20% of the handled material was shaved off, mainly as fine material, so 24% more was handled than appeared in the bundles. Productivity could be raised to 24 bundles per E_0 with logging residues, but with young stems the productivity may be 50% lower. Forwarding bundles was at least 2.5 times more productive than forwarding loose logging residues.

In conclusion, bundling could be of interest when economical and environmental aspects of the whole chain are considered.

Keywords: wood energy, shave-off, forwarding

1. Introduction

A formerly widely used system for procuring fuel wood in Sweden and Finland incorporates fuel adapted harvesting at clear cuts, forwarder extraction of logging residues and their piling at landings as storage areas (Andersson et al. 2002). This system has several drawbacks.

Three basic chains for bio fuel handling can be used; (i) Maintain pieces whole and chip them just before use, or (ii) compact the material as bales or bundles, or (iii) chip as soon as possible. All chains have some drawbacks. The second chain needs extra machinery from beginning to collect plus compact the pieces to better handling units, and the third chain needs a chipper at least from the landing, so storing losses may occur. In the second case long distance transport costs may be reduced compared to not treated slash (Johansson et al. 2006, Engblom 2007, Spinelli et al. 2012), but the extra cost for specialised machines is not favoured in the practise although transport distances of more than 60 km may need some compaction of the logging residues to be of economic interest (Johansson et al. 2006, Engblom 2007).

Both time and financial costs are high when collecting logging residues after clear-felling, or small stems following a first commercial thinning (Brunberg 1991, Hakkila and Nurmi 1997, Eliasson 1998, Cuchet et al. 2004, Kärhä and Vartiamäki 2006, Jylhä and Laitila 2007). A possible way to reduce the cost of harvesting of small stems is to utilise whole trees (Hakkila 1989), especially in combination with multi-tree handling machines (Brunberg et al. 1990). At extraction of slash, the maximum load on forwarders and lorries is only 35–50% (7–8 tonnes on a 16 tonne forwarder or

14 tonnes on a 40 tonne truck) of the vehicles bearing capacities and the transportation costs are high if logging residues or small trees are not compressed (Carlsson et al. 1983, Brunberg et al. 1998, Johansson et al. 2006). A possible solution is to compress the material into bundles at an early stage in the logistic chain. The advantage of this is that a small bunch of trees or logging residues can be kept together from the forest to the factory where the bunch can be processed (Schiess and Yonaka 1982, Arola et al. 1985, Flinkman and Thörnqvist 1986, Johansson et al. 2006, Spinelli et al. 2012). These bundles may also be used as storing units (Pettersson and Nordfjell 2007). Small bunches can be handled during transportation with the same equipment as industrial cut-to-length round wood (Schiess and Yonaka 1982, Liss 1995, Johansson et al. 2006). The bundles can be compressed using a number of methods, and the forces needed to compress the residues and small trees into fairly dense bundles are actually quite small (cf. Nordfjell and Liss 2000).

Besides logging residues, forest fuels from powerline corridors comprise a potential resource that has been largely neglected to date. Lanes wider than 5 m cover approx. 140,000 hectares of productive forestland in Sweden (Anon.1989), and every year approx. 13,000 hectares of lanes are cleared (Jonsson et al. 1992). Silviculture in these lanes is aimed at maintaining the power lines reliability and to facilitate their maintenance. For example, the power company Skellefteå Kraft in Sweden has 12,000 km of lanes, including 1,000 km of 40–metre broad 130 kV power lines. These lanes are coppiced every 12–20 years when the trees are 3–5 m tall, and their diameter at stump height is 4–8 cm. Coppicing can be carried out motor-manually by brush-saw during the snow-free season at a cost of 160–300 €/ha (Larsson 1998). Furthermore, a 3-metre broad inspection track and 2-m radius circles around each pole are kept completely free from brushwood. The cost of all these activities may account for more than half of the total maintenance costs for the power lines.

A rather new procurement approach that has been introduced, and may still be under development, involves compacting logging residues into cylindrical bales known as composite residue logs (CRL, cf. Andersson et al. 2002). There are currently six major types of equipment on the market for compressing logging residues. Three of them (Fiberpac, Fixteri and Pika RS 2000) compress the material through a funnel, tie strings around the bundle and finally cut the bundle to the desired length, e.g. 3–4 m (Brunberg et al. 1998, Kärhä and Vartiamäki 2006). The fourth type (WoodPac) tumbles the material within a compartment with spiked rollers, which shave off some of the fine material (mainly needles and twigs) and produces 3.4 m long bundles. Finally, strings are tied around the bundle, which is then released from the compartment and falls to the ground. The fifth, older type is baling (Bala Press AB), which heavily compresses logging residues into 1.2×1.2 m cylindrical bales (Andersson and Hudson 1997), is hard to chip due to the size. The baling and bundling is done at the harvesting site to facilitate handling for transporting the forest fuel. The sixth type is a lorry mounted compression unit, which compresses with high forces up to 4.8 m long bundles (Lindroos et al. 2010). Productivity may be quite high but the applied forces are far above those needed for the material and need terrain transport of loose material.

Preliminary calculations indicate that the transport benefits could well justify the costs involved in bundling the logging residues (cf. Johansson et al. 2006, Engblom 2007, Spinelli et al. 2012).

The WoodPac bundling system seems to have been studied least intensively of these six approaches. It is also of interest since it releases some of the fine material back to the forest. This shaving off of needles and twigs is likely to have both advantages and disadvantages. Advantages include the facts that disproportionately high amounts of nutrients will be left in the forest, since the fine material contains relatively high levels of nutrients, and the heating plant will receive less troublesome minerals in the ash (cf. Orjala et al. 2000, Aho and Silvennionen 2004). The disadvantage is that the shaving will most likely reduce the productivity of the machinery.

WoodPac is a hydraulically driven machine that is placed on and powered by vehicles, such as a medium-sized forwarder. The mass of the WoodPac machine is about 7.6 Mg and the hydraulic power unit should be able to pump 2 – 2.3 l s^{-1} generating 28–32 MPa pressure. The compression space contains eight cylinders, two of which are equipped with spikes. The bundles produced are 3.4 m long and have a radius of about 0.7 m.

Some few large-scale productivity studies have been undertaken on these bundling machines (Kärhä and Vartiamäki 2006) and preliminary calculations on the benefits associated with bundling have been based on limited material. One issue to address is how concentrating the fuel material in heaps on the clear-cut area affects the bundling. Further parameters that need to be investigated are the amounts of fine material that are released by the WoodPac machine, and the benefits (if any) of this material for the forest soil. An additional question to consider is whether the bundling equipment can bunch small trees that are longer than the compartment. Finally, studies to date seem to have concentrated on the production of raw material, and little information has been gathered on the amount of energy contained in the bundles produced.

2. Aims

The aims of the study were to measure the productivity of bundling with a WoodPac machine, to assess the effects (if any) of the concentration of forest fuel on productivity and to evaluate possible differences in productivity between bundling logging residues and small stems. The amount of material shaved off and the energy content of the bundles were also considered in the productivity analyses.

3. Material and Methods

3.1 Description and preparation of experimental sites

Material from three locations was used: two clear-felled area and a power line corridor. Logging residues were collected at a final felling stand 15 km west of Umeå (lat. 65.51 N, long. 20.17 E) and a final felling mid-south of Sweden (Sävsjö, Småland, 57° 25´N; 14° 40´O). The first stand (ca. five ha in area) was harvested at the end of May, and 221 m^3 solid volume under bark/ha (sub ha^{-1}), comprising 66% Norway spruce (*Picea abies (*L.*) Karst.)*, 32% Scots pine (*Pinus silvestris* L.), and 2% deciduous trees, was extracted according to the log list from the harvester. The minimum top diameter for pulpwood was 5 cm. The stand was 130 years old and naturally regenerated. The second stand was a 0.58 ha 120 yr-old spruce stand, cut in autumn. The tree harvester operators were instructed to perform fuel-adapted harvesting, that is trees were to be delimbed at the side of the machine and the residues were not to be driven on. The two forwarder operators were also instructed not to drive on the piles of residues when extracting timber. After harvesting, the piles were left to dry for a month. The average basal area of the 552 piles produced was 4.06 m^2 (s. dev. 1.4), assuming that the basal area formed a circle, and the average height was 0.76 m (s. dev. 0.18), so the average volume was about 1.5 m^3.

The third location was a power line corridor, 100 km N Umeå (lat 64.28 N, long 21.17 E), which was examined during a cleaning operation. About 500 m of the 40 m wide corridor was used for the study. All trees (0.5 to 6 m tall) were felled motor-manually on the 22nd and 23rd of May 2002, and the coppicing crew were instructed to fell trees perpendicular to the power line to allow them to be easily picked up by the bundling machine. The regeneration was a mixed birch (60%) and pine (30%) stand with 8,000 stems ha^{-1} and, according to calliper measurements, an average diameter at breast height (Dbh) of 1.7 cm (four circular plots). Some larger pines with Dbh 6.5 cm were also present. Bundling was done along a route in the area selected to reflect the different densities of young trees.

3.2 Bundling

Bundling was done with a 2001 version WoodPac unit mounted on a Rottne SMV Rapid 13.5 Mg forwarder with a Rottne RK 90 crane equipped with a

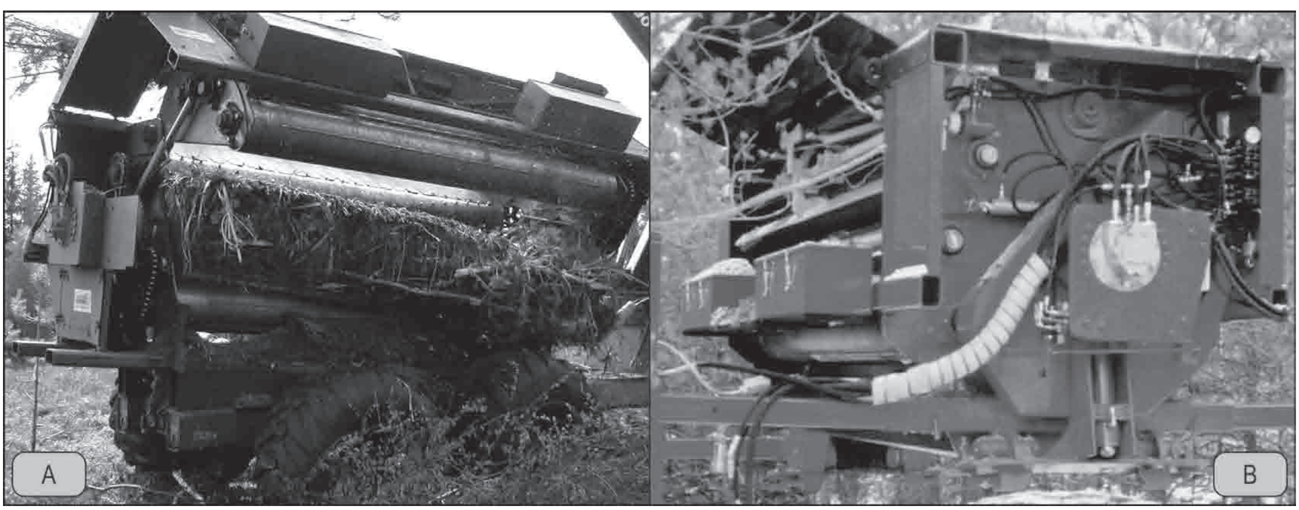

Fig. 1 Woodpac during release of the compression chamber. (A) Fabricated CRL can be seen in the foreground. From the power line; (B) Front frame of WoodPac. (Photo: I. Wästerlund)

Hultdin 28 slash grapple. The operator had had several years of experience with this machinery. The eight WoodPac rollers are driven and connected with a transmission chain to ensure they all rotate at the same speed (Fig. 1A and 1B). Material is fed in by crane into a slot between the two top rollers. The width of the feeding slot restricts the diameter of the material to less than 30 cm. The top rollers are spiked and rotate in opposite directions to allow the material to be fed into the compression chamber. As material is fed into chamber, the rolling binds the material together, forming a CRL. Once the operator judges the chamber to be full, a twine dispenser feeds polypropylene agricultural twine between the rollers on three different places on the bundle. When the tying process is complete, the twine is automatically cut. The process is then manually stopped to allow the chamber to open and the CRL to be ejected.

The mass of each CRL was determined when loading the CRLs onto the forwarder with a TB 3000 crane-mounted scale, calibrated each day with a concrete weight (mass 588 kg). CRLs were carefully gripped in the middle and the mass was read when the CRL was in balance and the display was steady. Following this procedure, the accuracy should be within ±5 kg, according to the specifications.

A 5% sample of the 552 piles of logging residues was randomly selected. From each of the 28 piles, an 8–10 litre sample of loose logging residues was collected in the middle of June.

The piles were chipped into a container with an Erjo 765 chipper. Samples were transported the same day to an accredited laboratory to analyse their moisture content at 105° C 24 h, according to Swedish standard method SS 18 71 70 (Anon. 1997). To test if the moisture content varied after bundling, samples were also taken from five bundles and measurements were done after chipping the whole bundles (Table 1). Moisture contents are given on a green weight basis.

Table 1 Moisture content measured in 28 heaps of logging residues before bundling, five CRLs after production and five CRLs composed of young stems after production. S. dev. = standard deviation

	Log. residues before bundling	CRL log residues after bundling	CRL young stem, after bundling
Av. moisture cont, %	28.6	24.3	23
S. dev.	4.4	5.2	2.5

3.3 Time studies

The operator of the bundling machine decided his own route through the clear-felled area, but was instructed to drive as normally as possible, since he had long experience in bundling.

The time study was done as a correlation study with snap-back timing (Anon. 1978), using a Husky Hunter computer running SIWORK3 software (Rolew 1988). The observation unit was one bundle i.e. from the time the bundler chamber was completely closed until it was closed again. Work with the bundling machine was split into eight work elements (Table 2). If more than one work element was performed simultaneously, the time for the work element with the highest priority was recorded. All element times were measured as effective times (E_0, Anon. 1978). Delay times were measured, but not included in the analysis.

Table 2 Description of time elements used to analyse bundling work

Priority	Work element	Description
1	Crane cycle	From when crane starts to move from the machine to grip material until the grip drops material into the bundler (or stops moving for other work to be done on the machine)
2	Feeding	Time when the grip is used to press down material into the bundler or the operator disperses material for the bundler
3	Tying	Time from when twine dispenser starts until the bundling chamber opens to eject a CRL
3	Unloading	From the time the chamber opens until it is closed again
4	Driving	From the time the wheels start to move until they stop or a higher priority element starts
5	Miscellaneous	Productive time used for other essential tasks
6	Bundling	Time when logging residues are being compressed and no higher priority work is being done
7	Bundler delays	Non-productive time caused by problems with bundling machine, not included in the study

Table 3 Work elements and priorities for the time study on forwarding bundles

Priority	Work element	Description
1	Crane out	From the time the crane starts to move from rest point to grip material until the grip grasps the material (or the crane is stopped for driving)
1	Crane in	From when the grip has grasped the material, and lifts it, until it drops it into the machine (or the crane is stopped, before the machine is moved to collect more material)
2	Re-gripping	Time when the crane moves to grip again, or carry more material within a crane cycle
3	Driving to area	Time from when the wheels start to move at the landing until they stop for material to be collected, or a higher priority element starts
3	Driving within area	From when the wheels start to move until the wheels stop or a higher priority element starts. Only includes driving within harvesting area
3	Driving to landing	From when the wheels start to move after the last crane cycle on the bundling area until the wheels stop at the landing, or a higher priority element starts. Only includes driving after leaving loading area, when machine is full
4	Miscellaneous	Time required for other essential tasks
5	Delays	Non-productive time, not included in the study

In the time studies, 250 bundles of logging residues and 22 bundles of young stems were analysed. After fabrication, the diameter of each CRL was measured at three places, 0.2–0.3 m from both ends and in the middle. The mean rear, mid-point and front-end diameters (s. dev. within brackets) of CRLs made of logging residues were 0.73 m (0.020), 0.74 m (0.020) and 0.73 m (0.019), respectively. For CRLs made of young trees, the corresponding figures were 0.75 m (0.046), 0.76 m (0.026) and 0.77 m (0.051). Each CRL was tagged at both ends and was marked with GPS coordinates obtained using a Magellan 320 receiver.

3.4 Forwarding

The terrain transport of the bundles was done with a 14 Mg Hemek Ciceron TD 81 forwarder with a Fiskars 71 crane within a few days after bundling. The grapple was a conventional Cranab 028. The forwarder loading area was 4.8 m^2. The observation unit for forwarding was a full load of bundles, i.e. from the time the wheels started to move from the landing until a new load of bundles was unloaded. The type and number of bundles taken for each load, and their order of loading, were noted to provide records of the distances travelled and the mass of the loads. The time elements used in the analysis are shown in Table 3. Four loads were analysed in this way.

3.5 Complementary studies Småland

To measure the amount of logging slash handled for each bundle, a separate study was done in Småland on the amounts of material that were shaved off. For this, the machine was placed on a tarpaulin while it produced one bundle. All biomass was then cleaned from the machine, which was moved away from the tarpaulin and the content was weighed. The prepared bundle was also weighed, numbered and positioned as usual. In addition, the number of crane cycles required to produce the bundle was counted as well as the time taken for tying and unloading it. The last two tasks were done as controls, since they were partially masked during normal operation. Eight bundles were analysed in this way (Bohm Larsson 2004).

To get a rough estimation of fuel consumption, the machines started with a full tank and the amounts required to refill them during or at the end of the study were recorded (Umeå study).

4. Results

Production data are based on the production of 1 Mg (green weight) CRLs on the ground. Moisture contents at the time of bundling were interpolated between moisture contents in the logging residue heaps and newly produced bundles (Table 1). The bundler produced 19.3 bundles per effective hour (E_0) from logging residues, with an average mass of 368 kg (Table 4). At a moisture content of 27%, the production was 5.2 Mg dry matter per hour (DM, dry mass per bundle, 270 kg). When bundling rather poorly dispersed young stems in the power line corridor, the productivity and production fell to only 10 bundles and 2.6 Mg dry matter per hour. Differences in productivity measured in terms of min per Mg and bun-

Table 4 Productivity when bundling logging residues and young stems with WoodPac (MC=moisture content, DM=dry matter)

	Green mass per bundle, kg	Min. per Mg, green weight	Bundles per E_0 hour	Mg DM prod per E_0 hour
Logging residues, MC=27%				
Average (*n*=250)	368	8.83	19.3	5.2
S. dev.	38.2	1.89	3.63	1.06
Young stems, MC=26%				
Average (*n*=22)	350	17.63	10.1	2.6
S. dev.	37.6	3.90	1.60	0.52

dles per hour depend on the mass of the bundles, since values were based on bundles.

The average effective time for slash bundling per Mg green material was 8.8 min (Table 5). For lifting the material in with the crane, it took about 50% of the time for bundling logging residues, and about 64% of the time for young stems. Compared to logging residues, the proportion of time consumed by driving during bundling was high for young stems, indicating that the concentration of the material could have great influence on this variable. Most other time elements seem to be quite consistent between the two types of material used, indicating that they could be machine-dependent. However, the substantial standard deviation obtained for tying time (which reflects delays that occurred in the bundler) indicates that the system could be improved.

Table 5 Average time consumption for each work element when bundling logging residues (n=250 bundles) with 27% moisture content, and young stems (n=22) with 26% moisture content. Standard deviations shown in brackets, and percentage of effective time in italic

Work element	Cmin per 1 Mg green log. residues, S. dev. and %	Cmin per 1 Mg green young st., S. dev. and %
Crane cycle	4.49 (1.02) 50.8	11.23 (2.80) 63.6
Feeding	0.95 (0.52) 10.7	1.18 (0.39) 6.6
Driving	1.03 (0.85) 11.7	2.47 (1.53) 14.0
Compression	0.75 (0.37) 8.5	1.04 (0.40) 5.9
Tying	1.00 (0.57) 11.3	0.98 (0.31) 5.6
Unloading	0.44 (0.09) 5.0	0.53 (0.11) 3.0
Miscellaneous	0.18 (0.30) 2.0	0.21 (0.24) 1.2
Effective time	8.83 (1.89)	17.63 (3.90)
Delay bundler	0.4 (1.67)	0
Total time	9.23	17.63

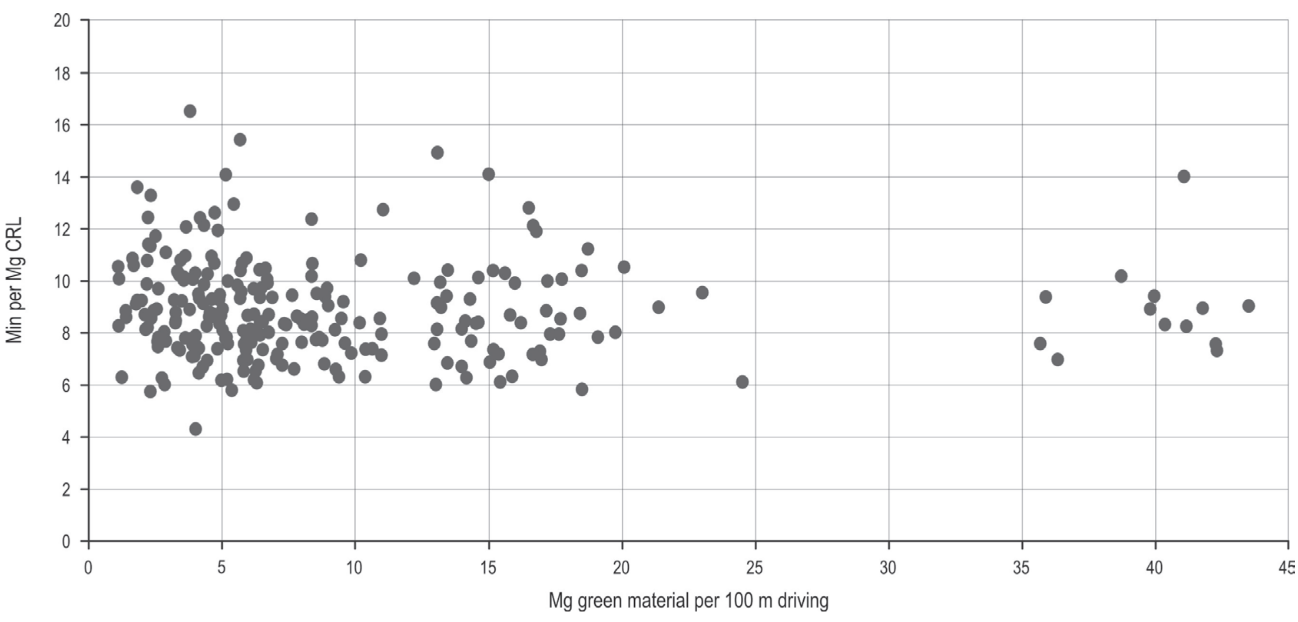

Fig. 2 Effective time required to produce 1 Mg of bundles plotted against distance driven to collect the material for the bundles produced with logging residues

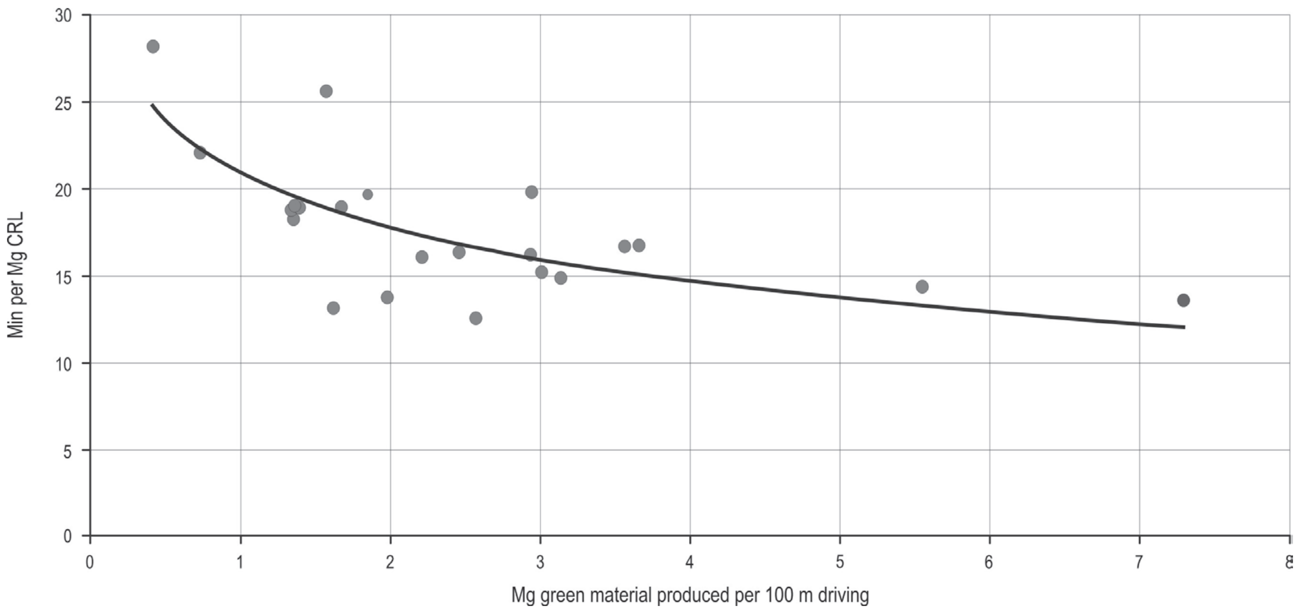

Fig. 3 Effective time required to produce 1 Mg of bundles plotted against the distance driven to collect the material to produce bundles with young stems ($r^2=0.52$)

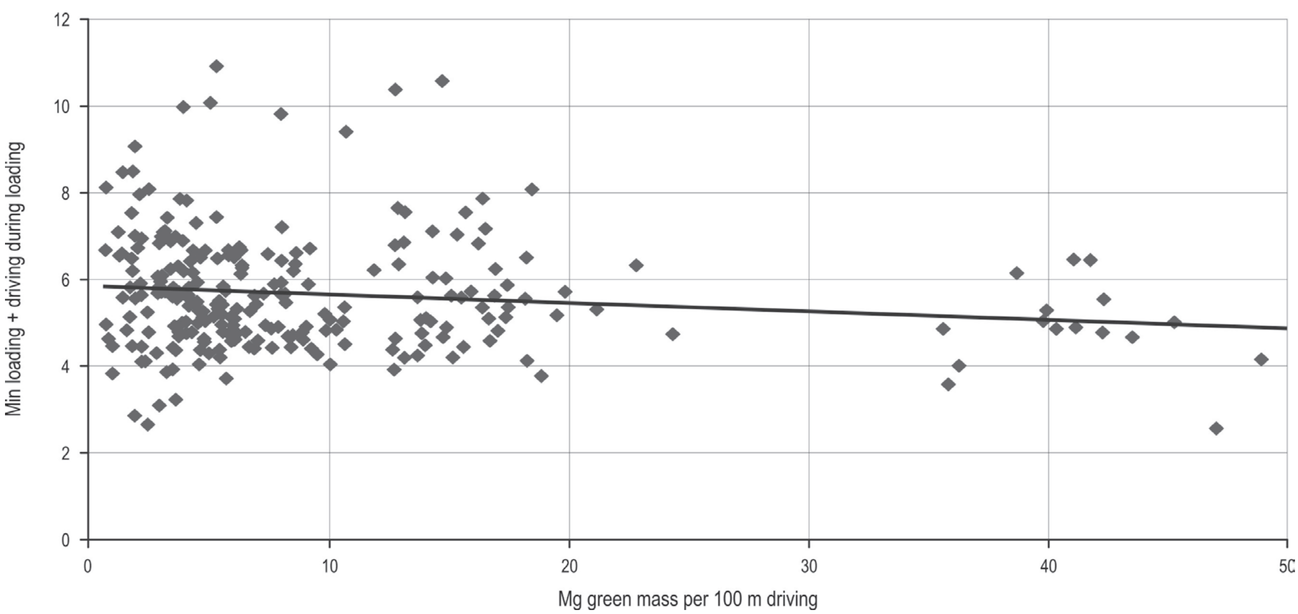

Fig. 4 Time for the work elements loading and driving during loading/bundling required to produce 1 Mg of bundles plotted against distance driven to collect the material for logging residues ($r^2=0.025$)

Although the time study indicated that there might be a weak correlation between the time required to make 1 Mg of bundles and the distance driven to collect the material, there seemed to be no such effect when collecting logging residues (Fig. 2). For young stems, on the other hand, production declines when the concentration of biomass is low (Fig. 3).

A variable that could be related to bundling productivity was concentration of the material (as indicated by the amounts produced per 100 m driven). The effective times for the measured work elements for bundling logging residues were randomly or non-significantly correlated to this concentration measure (Fig. 4). However, for young stems, two elements –

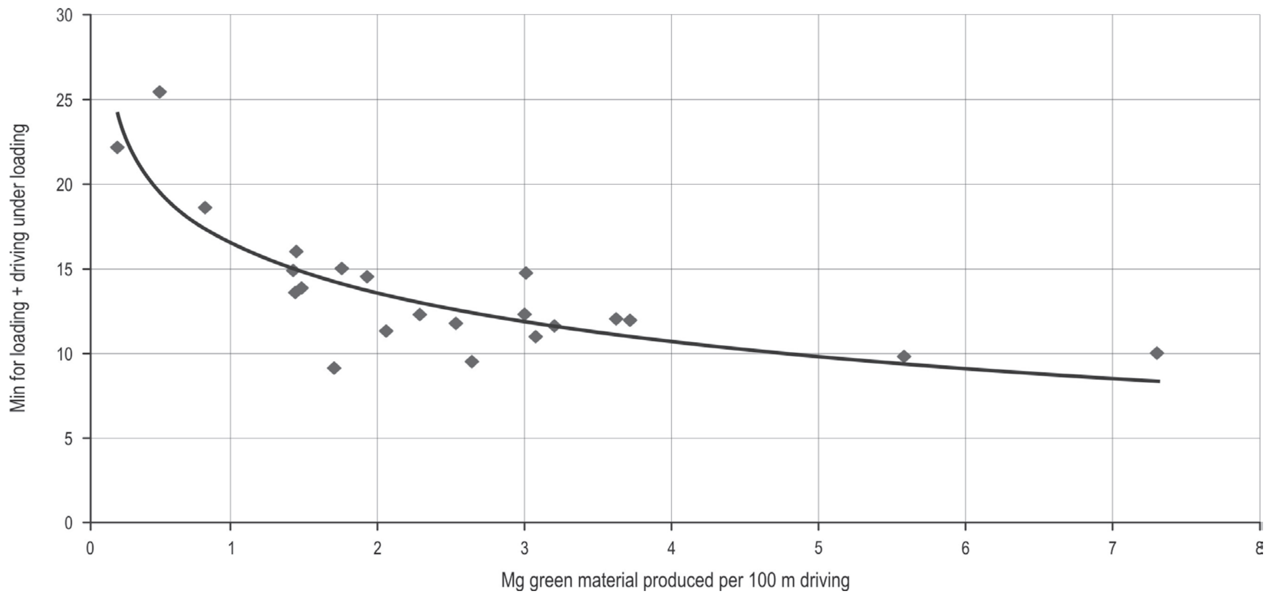

Fig. 5 Time required for the work elements loading and driving during loading to produce 1 Mg of bundles compared with distance driven to collect the young stems ($r^2 = 0.71$)

crane work (loading) and driving during loading – were strongly related to production, indicating that productivity would be significantly decreased at concentrations less than about 5 Mg material produced per 100 m driven (cf. Figure 5).

In the shaving study, the amount of fine material shaved off while bundling logging residues was 96 kg (s. dev. 19), and the green mass of the prepared bundles was 402 kg (s. dev. 25). Thus, the machine handled 1.24 times more material than the amount bundled, implying that to produce 370 kg bundles, as in this part of the investigation, 456 kg of material had to be handled on average (Fig. 6).

Forwarding the bundles was investigated only as a case study. The average load for the four trips examined was 12 bundles, and the forwarding distance was on average 280 m per trip. Since the bundles were quite dry, the average mass per load was only 5 Mg but the average volume was 16 m^3 (full forwarder load = 16.3 m^3). The average effective time for forwarding was 3.9 cmin per Mg green mass, equivalent to 15.6 Mg per E_0 (Table 6). These productivity figures are not high compared to timber forwarding in terms of mass, but in volume terms they are very high (cf. Fig. 7).

The amount of fuel consumed was 292 litres when bundling logging residues, giving an average con-

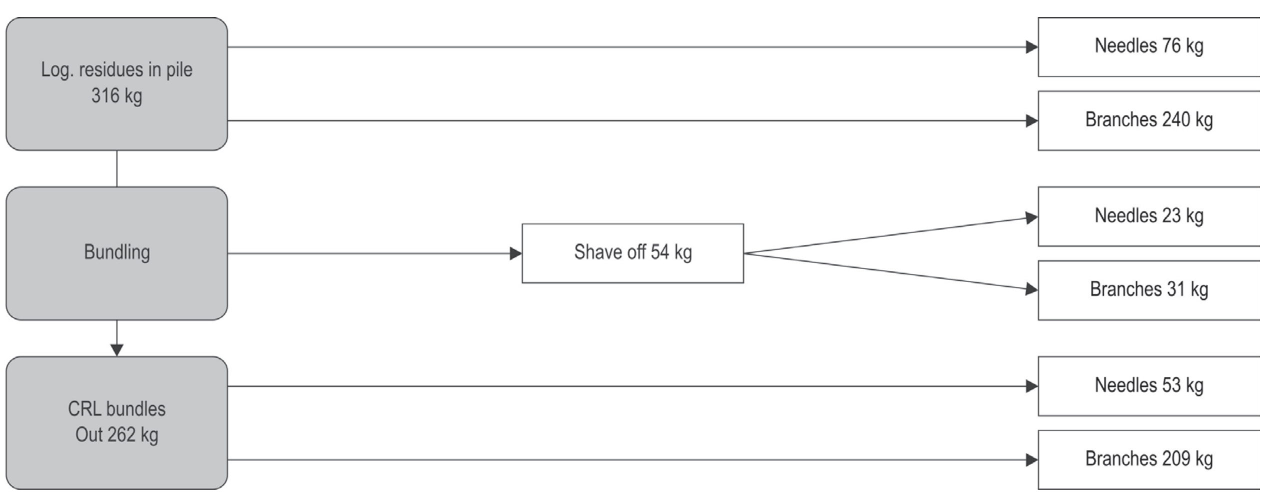

Fig. 6 Composition of material flow (kg DM) when producing one bundle including the peeled off material (Smland material)

Table 6 Average time consumption in cmin per Mg green mass and per unit volume for each work element when forwarding CRLs with 27% MC. Standard deviations shown in brackets

Work element	Cmin per 1 Mg green mass	Cmin per m^3
Crane out	0.60 (0.02)	0.18 (0.005)
Crane in	0.68 (0.01)	0.21 (0.003)
Driving during loading	0.95 (0.40)	0.29 (0.123)
Driving loaded	0.48 (0.16)	0.15 (0.048)
Gripping	0.10 (0.21)	0.03 (0.065)
Re-gripping	0.01 (0.01)	0
Driving empty	0.89 (0.26)	0.27 (0.079)
Miscellaneous	0.19 (0.09)	0.06 (0.029)
Effective time	3.89 (0.51)	1.19 (0.168)
Delays	0	
Total time	3.89	1.19

sumption of about 23 litres per hour. During forwarding, the fuel consumption was 13 litres. This means that the fuel consumption was about 23/19.3=1.2 litre/bundle during bundling residues and 13/(4*12)=13/48=0.3 l forwarding per bundle.

This means that (1.21x9.7)=11.7 kWh diesel were consumed to produce a bundle with logging residues worth (19.7x0.27)/3.6=~1.5 MWh and 65 litres were consumed to make 22 bundles (65/22=2.95 l/bundle),

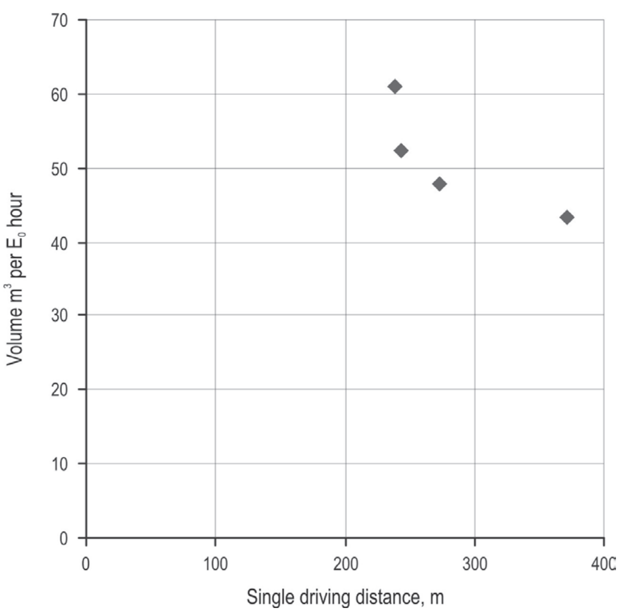

Fig. 7 Productivity when forwarding CRLs in terms of transported volume for a single driving distance

with the young stems with an energy content of about 19.7x260x1/3600=1.42 MW, and (0.3x9.7)/1.42=2 kWh diesel consumed to forward a bundle and per produced MWh bundle. Thus from the energy point of view, bundling of young stems in unorganised collection cannot be motivated.

The energy content in each bundle (19.7 MJ/kg DM) is based on calorific values from Pettersson and Nordfjell (2007).

Energy content in diesel is set to ~9.7 kWh/litre for environment class 1 diesel, which is commonly used for forestry machines in Sweden.

5. Discussion

One drawback of this study was that the material had unusually low moisture contents because the weather was warm and dry (so both the logging residues and young stems dried out rapidly) in the delay between harvesting and bundling. In colder, moist conditions, the green residues may have moisture content around 50% (cf. Hakkila 1989). In such cases the bundles could have a green mass of about 540 kg and a dry mass about the same as found here.

The working practices in the study on young stems were not ideal, since the stems were scattered on the ground, and the productivity figures presumably reflect this. The figures obtained may indicate the productivity for motor-manually cleaned areas, but the young stems should preferably be bunched before bundling (cf. Johansson and Gullberg 2002), which would probably considerably improve the production. However, the experiment showed that it was possible to feed in stems up to about twice the length of the chamber. If the stems were just a little longer than this, there was no need for the operator to do anything more than place the root end to one side of the chamber. Some long trees (5–6 m) had to be broken up with the grapple after some time causing increased bundling time (cf. Table 4).

Production data were based on times recorded per bundle, and the locations of the bundles produced. The amounts of the basic material of logging residues in the heaps, and their locations, were not recorded, so the productivity could not be related to the heap size. On the other hand, the distance travelled to produce a bundle should indicate the available amounts of material reasonably well.

The GPS marking of the bundles may have had an accuracy of ±15 m. The accuracy is greater if the GPS receiver (Magellan 320) is placed on the same spot for a while than if a very rapid reading is taken. In this case, the receiver was left on the bundles for 30–35 s to ensure that the spot determinations were as accurate as possible, at that time**.** The positions from the receiver were transferred in NMEA and then converted to RT90 using the program GPS Pathfinder Office 2.70. A constant height of 60 m above the ellipsoid WGS84 was assumed at conversion.

The productivity of the WoodPac machine was 19.3 bundles with logging residues per E_0hour, but there was substantial variation in time expenditure between the best and worst bundles. The average effective time for the 10 best bundles was about 6 min per Mg (25 bundles per E_0) and 14 min for the 12 worst, indicating that improvements can be made to both the work method and the machine (cf. discussion in Kärhä and Vartiamäki 2006). Differences between the 10 best and 10 worst bundles did not depend on the available amounts of material per 100 m, but there was a threefold spread in time consumption for each of the elements feeding, driving during bundling, tying and miscellaneous. More detailed studies on these work elements and conditions are needed to identify the reasons for the large differences observed. Delays occurred in the work element tying for several reasons, e.g. sometimes the twine broke, sometimes the tying was disrupted by branches sticking out from the bunch and sometimes the string did not attach to the bundle. Improvements to the machine are already being made to reduce the time requirements for this work element from 30 s to about 19–20 s per bundle.

The average bundle in the present study contained about 270 kg DM biomass. With an average energy content of 19.7 MJ kg^{-1} (Pettersson and Nordfjell 2007), each bundle would contain 1.48 MWh and the production per hour could amount to 28.9 MWh.

Andersson and Hudson (1997) reported that the Bala Press baling machine could produce 17–18 bales per E_0 hour when baling material, at stump site, with moisture contents similar to those in the present study. The energy content was 1.6–1.7 MWh per bale, indicating productivity per hour of about 29 MWh, similar to that found for the WoodPac.

Andersson et al. (2000) and Kärhä and Vartiamäki (2006) describe studies in which both Fiberpac and WoodPacmachines were examined, and the WoodPac data they provide are about consistent with the results obtained in the present study. The Fiberpac machine was found to produce 18–35 bundles per effective hour in the cited studies. The bundles produced by Fiberpac and WoodPac machines are about the same size, but Fiberpac bundles may be less compressed (0.98 MWh per bundle according to Kärhä and Vartiamäki 2006). Assuming that the DM content in the Fiberpac bundle is 250 kg for similar material as above, Fiberpac would then produce 27–47 MWh per E_0 (productivity figures of 10–30 bundles per $E_{15}$are indicated in the Timberjack brochures, Anon. 2003). However, Kärhä and Vartiamäki (2006) state that the productivity is greatly influenced by the quality of residue piles and windrows, as was also found in the present studys. Spinelli et al. (2008) report a production of 25 green ton/h when bundling poplar trees on a poplar plantation (11 DM ton/h at 55% moisture content). The Fixteri bundler produced 2.8–3.7 m^3 with mainly small stems (17–89 litres/sten) at first thinning (2.56 m long, around 50% in moisture content and roughly 325x0.5x19.7/3600 = 0.89 MWh), which is much less than WoodPac but, on the other hand, it cut the stems (Jylhä and Laitila 2007). Rogbico produced 25–38 MWh per machine hour, which is much more but, on the other hand, all material was already transported to the landing (forwarding logging residues took all the profit from the bundling according to Lindroos et al. 2010)

However, the WoodPac machines handle 24% more material than the amount produced as bundles. This decreases the difference in the amount of logging residues handled per hour between the two bundling systems. WoodPac tumbling and shaving procedure also appears to take about 15–20% more time than the Fiberpac compaction process. On the other hand, 20% of the fine material is left in the forest when using WoodPac, which could be advantageous (see below).

The low production with young stems may be caused, to some extent, by the fact that some trees had to be bent in back to the chamber, but the major problem in this case was definitely the low biomass concentration on the ground. The trees were simply spread out, albeit in one direction, after the motormanual cleaning and bundle production of only 2.5–3 Mg DM per E_0 hour may be significantly lower than potential figures. The only clear effect of biomass concentration was found in this part of the study: at more than 5 Mg green material produced per 100 m driven, time consumption stabilised at around 14 min Mg^{-1}. This indicates that a production rate of 4.3–4.4 Mg per hour could easily be achieved with better concentration of young stems, which should be confirmed in further studies, which is similar to production reported for mountain forests and maritime pine (Cuchet et al. 2004, Spinelli et al. 2012).

The forwarding productivity (15.6 Mg per E_0) was only moderate (but comparable to reported figures, Johansson et al. 2006, Kärhä and Vartiamäki 2006), relative to handling logs, if only the transported mass is considered. However, the CRLs produced filled up the forwarder bunk. For handling loose logging residues with single travel distances of 280 m (the average distance in the present study), normal productivity would be about 15 m^3 per hour (Hakkila and Nurmi 1997). According to Brunberg et al. (1998) forwarding productivity may be equal to about 8.5 green Mg per E_0 at distances of 280 m (adjusted for the moisture content found here). In the present case, the volume of the loads was about 16 m^3, indicating terrain transport productivity of about 50 m^3 per E_0. Bundling logging residues would thus improve the efficiency of terrain transport more than 2.5 fold, as indicated by Andersson et al. (2000).

5.1 Suggested improvements

On average, seven crane cycles were required to produce one bundle with a 0.26 m^2 grapple. An interesting question to address is whether a bigger grapple on the base machine would result in shorter feeding times, in spite of the rather small inlet slot. With a bigger grapple, the concentration of the material could have more effect.

The best figures obtained suggest that, with improved working techniques, it should be possible to attain the time consumption levels indicated in Table 7. Feeding of young stems would, of course, be improved using material collected with a feller-buncher, but long stems would undoubtedly need more handling compared to logging residues. Production of 24 bundles per E_0 hour would be attainable, indicating an E_{15} production of about 20 bundles, but only half this number with young stems.

5.2 Environmental aspects

The machine consumed 292 litres of diesel while producing 250 bundles, equivalent to roughly 1.2 l per bundle, when bundling logging residues. Thus, the bundling costs in terms of energy expenditure were equivalent to about 0.8% of the energy content of the prepared bundles. The fuel consumption of forwarding the bundles was estimated to be 13 litres, equivalent to 0.27 l per bundle and 0.18% of transported energy. If transporting loose logging residues, the machine would spend three times more time, and the energy expenditure could amount to 0.5–0.6%. Thus, more than half of the energy consumed for bundling is recouped solely by the reductions in energy costs for forwarding. Based on data from Bohm Larsson (2004) about 25.3 kg/ha of nitrogen, 3 kg of phosphorous, and 10.6 kg/ha of potassium were left on the spruce clear-cut area thanks to the shave off, which is worth quite a lot if replaced with the bought fertilizer.

Nevertheless, the tumbling and shaving action will inevitably take some time, placing the WoodPac system at a disadvantage relative to both the Fiberpac and Bala Press processes. The work elements »driving+bundling« and »compression« account for 20% of the time. As discussed above, this is roughly equivalent to the time difference between the WoodPac and Fiberpac production techniques. According to Rheén (2004) branches of young spruce trees may have an ash content of 2.12%, and according to Nurmi (1993), the foliage contents may be as high as 2.2–8.7%. The high levels of inorganic substances in the needles may cause problems during combustion (Orjala et al. 2000, Aho and Silvennionen 2004) and it may be better to leave them in the forest. Thus, the lower bundling productivity obtained with WoodPac could be compensated by producing bundles of higher quality due to lower ash contents, and perhaps better drying properties (Jirjis and Nordén 2002, Pettersson and Nordfjell 2007), but these possibilities are still to be proven and evaluated (cf. Asikainen et al. 2002). Risks related to reductions in long-term site productivity and costs of ash recycling may also be reduced by using the WoodPac system (Burger 2002, Hakkila 2002). The catchment of material in the forest would be reduced but, on the other hand, the losses accrued during storage handling and transports could also be reduced with the shaving technique.

An important question to consider is how much the potential reduction in transport costs, reductions in the amounts of nutrients taken from the site, better drying capacities and better fuel are worth. If a high price-weighting is attributed to these factors (or possibly any price), it could even be worth increasing the proportion of material shaved off, either by prolonging the tumbling or by equipping the rollers with sharper or longer spikes.

Table 7 Possible effective times for production of 1 Mg green material with 50% moisture content using the WoodPac bundler

Work element	Cmin per 1 Mg Logging res	Cmin per 1 Mg Young stems
Crane cycle	2.43	5.55
Feeding	0.52	1.01
Driving + bundling	0.42	1.04
Compression	0.45	0.69
Tying	0.42	0.42
Unloading	0.28	0.31
Miscellaneous	0.13	0.14
Effective time	4.65	9.16
Bundles per E_0	24	12

6. Conclusions

The studies have shown the following results:

⇒ The WoodPac machine produced 19.3 bundles with logging residues per E_0, equivalent to 28.5 MWh.

⇒ The productivity was not influenced by the amount of green mass, as long as there was more than 5 Mg per 100 m driving distance and the material was collected from heaps.

⇒ Productivity can be improved by about 20% for logging residues.

⇒ Young stems longer than the compartment can be bundled, but their bundling may take twice as long as bundling logging residues. Bunching stems before using the bundler may considerably improve the production, and this possibility needs to be studied.

⇒ About 20% of the handled material was shaved off, mainly as fine material, and left in the forest, leaving some NPK back to the forest.

⇒ Forwarding productivity was improved at least 2.5 fold with bundles compared to forwarding loose residues.

⇒ Energy expenditure for bundling and for forwarding the bundles at a distance of 280 m was equivalent to about 0.8% and 0.2%, respectively, of the energy content of the bundles produced.

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